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ORIGINAL PAPER

A weeding-duration model for *Abies sachalinensis* plantations in Hokkaido, northern Japan

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Abstract: I developed a weeding-duration model for Sakhalin fir (*Abies sachalinensis* (Fr. Schmidt) Masters) plantations that employs a generalized linear model. The number of years following planting that weeding is necessary is the response variable, and elevation, slope steepness, maximum snow depth, annual precipitation, geology, soil, site index, slope aspect, and vegetation type are explanatory variables. Among the explanatory variables, geology, soil, slope aspect, and vegetation type are categorical data. A Poisson distribution is assumed for the response variable, with a log-link function. Elevation, slope steepness, maximum snow depth, annual precipitation, site index, and vegetation type had a significant effect on weeding duration. Among the eight models with the smallest Akaike information criterion (AIC), I chose the model with no multicollinearity among the explanatory variables. The weeding-duration model includes site index, maximum snow depth, slope steepness (angle) and vegetation type as explanatory variables; elevation and annual precipitation were not included in the selected model because of multicollinearity with maximum snow depth. This model is useful for cost–benefit analyses of afforestation or reforestation with *Abies sachalinensis*.

Key words: *Abies sachalinensis*; plantation; snow depth; site index; weeding

Introduction

In Hokkaido, the northernmost main island of Japan, many artificial forests of Japanese larch (*Larix kaempferi* (Lamb.) Carr.) and Sakhalin fir (*Abies sachalinensis* (Fr. Schmidt) Masters) were created from the 1950s through the 1970s to meet increasing demand for timber. Many stands planted in that era are now ready for harvest. However, low timber prices and the increasing cost of seedlings (Hokkaido Forestry Seeds and Seedlings Association 2001–2010) and forestry labour have made forestry in Japan less profitable. Therefore, some forest owners are reluctant to reforest after harvesting.

In private forests in Hokkaido, Japanese larch is most widely planted tree, followed by Sakhalin fir. Use of shoulder brush cutters rather than herbicide is common in Japan for site preparation and weed control. Forest practice systems for Japanese larch (Hokkaido Forestry Research Institute 2007) and Sakhalin fir (Hokkaido Forestry Improvement and Spreading Association 1988) have been developed and applied to stand density management, including systems related to planting density and thinning for each site quality class.

However, there had been no model for weeding for these species. Thus, in a cost-benefit analysis model of plantations, the same number of years of weeding (e.g., 5 years) has been used in all stands of Japanese larch and Sakhalin fir. A weeding-duration model can aid in developing a standard system of forest practices that includes not only stand density management but also the number of years that weeding is needed. For Japanese larch, a weeding-duration model was recently proposed by Nakagawa et al. (2011), which assigns weeding-durations to reflect environmental characteristics of each stand. A similar weeding-duration model is desirable for Sakhalin fir, the second most widely planted species in Hokkaido.

Methods

I obtained data on applications for afforestation and reforestation subsidies for private forests in Hokkaido from the Forest Development Division, Bureau of Forestry, Hokkaido Government. I chose plantations of Sakhalin fir planted in 1991 and investigated the number of years in which subsidies for weeding were granted. The data included 786 Sakhalin fir stands, with an average size of 1.62 ha and a range of 0.01–21.20 ha. There were no applications of weeding subsidy for discrete years. When applications for a weeding subsidy had stopped, I considered this to be the

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end of weeding in a stand because almost all (96.6–99.8%) weeding in private forests of Hokkaido has been subsidized by national and local government funds in recent years (Forest Development Division 1991–2009). I assumed that weeding operations were continued only for the years necessary because private forest owners and government inspectors of subsidies for private forests are very cautious in their investment in forestry. Excessive weeding is avoided to eliminate unnecessary expense, but weeding for too short a period is also avoided to secure good growth of the planted trees.

For all Sakhalin fir plantation stands in Hokkaido planted in 1991, information about the elevation, slope steepness, and slope aspect was obtained from the Geographical Survey Institute, Ministry of Land, Infrastructure, Transport and Tourism (2010). Maximum snow depth and annual precipitation data were obtained from the Japan Meteorological Business Support Center (2010), and information on geology and soil was provided by the National and Regional Planning Bureau, Ministry of Land, Infrastructure, Transport and Tourism (2011). The site index assigned to each city, town, or village (Japan consists of 47 prefectures, divided into cities, towns, or villages, with no unincorporated areas) was calculated by averaging site indices of surveyed plots in that particular locality. Data about maximum snow depth and annual precipitation obtained from the Japan Meteorological Business Support Center are average values for a 1-km mesh from 1971–2000. Vegetation types are reported in applications for subsidies, and four types were used in the analysis: *Sasa nipponica* Makino, *S. senanensis* Rhed., *S. kurilensis* Makino et Shibata, and other weeds.

Factors affecting the number of years that Sakhalin fir plantations required weeding were analyzed using a generalized linear model. The number of years that weeding is necessary was the response variable, and elevation, slope steepness, maximum snow depth, annual precipitation, geology, soil, site index, slope aspect, and vegetation type were explanatory variables. Among the latter, geology, soil, slope aspect, and vegetation type were categorical data. A Poisson distribution was assumed for the response variable, and a log-link function was applied because it is a canonical link function for Poisson distributions (Faraway 2006).

Table 1. Average, standard deviations, and ranges for continuous variables

Variable	Average	Standard deviation	Range
Number of years that weeding is necessary	7.19	2.17	1–11
Elevation (m)	148.40	111.47	7–762
Slope (degree)	10.53	4.71	0–26
Maximum snow depth (cm)	98.14	44.68	20 –271
Annual precipitation (mm/year)	1,270.83	199.42	696–2,215
Site index (meters at 30 year, for city, town, or village)	13.56	1.29	9.35–16.51

Averages, standard deviations, and ranges of continuous variables are shown in Table 1; Tables 2–5 contain summaries of categorical variables. I first tested whether the effect of each explanatory variable is significant using generalized linear models, with a level of significance of 0.05. Models were constructed using all combinations of explanatory variables. Among the eight constructed models with the smallest Akaike information criterion (AIC), a model was chosen in which all signs of coefficients for explanatory variables were the same as that in the model with a single explanatory variable.

Table 2. Summary for geological type of stands

Category	Number of stands
Gravel and sand	53
Sand, gravel, and clay	24
Detritus	11
Gravel, sand , and clay	85
Peat	7
Conglomerate	15
Sandstone	42
Pyroclastics	17
Loam	40
Pumice flow deposits	31
Volcanic breccia and tuff breccia	49
Tuffaceous rocks	42
Rhyolitic rocks	8
Andesitic rocks	51
Basaltic rocks	7
Granitic rocks	7
Diabasic rocks	7
Mudstone – Tertiary	107
Alternation of sand stone and mudstone - Tertiary	117
Sandstone and conglomerate - Pre Tertiary	12
Mudstone–Pre Tertiary	11
Slate – Pre Tertiary	15
Alternation of sand stone and mudstone – Pre Tertiary	17
Other	11

Table 3. Summary for soil type of stands

Category	Number of stands
Volcanogenous regosols	16
Volcanogenous regosols (coarse textured)	58
Brown lowland soils	27
Brown lowland soils (coarse textured)	29
Gray lowland soils (fine textured)	10
Gray lowland soils	8
Gray lowland soils (coarse textured)	6
Gley soils (fine textured)	8
Lowmoor peat soils	9
Thick ando soils	24
Ando soils a	49
Ando soils b (loam)	24
Regosolic ando soils	51
Gleyic regosolic ando soils	9
Light colored ando soils a	15
Light colored ando soils b (loam)	28
Brown forest soils I	9
Brown forest soils II	270
Brown forest soils III	7
Brown forest soils IV	17
Brown forest soils – ando soils	66
Gray upland soils	21
Other	25

Table 4. Summary for slope aspects of stands

Category	Number of stands
North facing	265
East facing	221
South facing	167
West facing	133

Table 5. Summary for vegetation types of stands

Category	Number of stands
Sasa nipponica	150
Sasa senanensis	421
Sasa kurilensis	13
Other weeds	202

Results

Among the explanatory variables, elevation, slope steepness, maximum snow depth, annual precipitation, geology, soil, site index, and vegetation type had a significant effect on the number of years that weeding is necessary (Table 6). The effect of slope aspect (p = 0.891) was not significant. As elevation, slope steepness, maximum snow depth, and annual precipitation increased, weeding duration also increased, while an increase in the site index led to shorter weeding duration (Table 6). Weeding duration was shorter on serpentine geology (n = 1, Table 2) and low-moor peat soils (n = 9, Table 3). The shortest weeding duration was with *Sasa nipponica*, followed by other weeds, *S. senanensis*, and then *S. kurilensis* (Table 6).

The eight models with the smallest AICs are shown in Table 7. Tolerances and variance inflation factors (VIF) of explanatory variables with continuous data are presented in Table 8. A tolerance of less than 0.10 or a VIF of 10 and above indicates strong multicollinearity (Quinn and Keough 2002), but no strong multicollinearities were found among explanatory variables (Table 8). However, estimated parameters for elevation were negative in the models with the seven smallest AICs, and annual precipitation was also negative in the models with the first, second, fourth, and sixth smallest AICs (Table 7). Because weeding duration increased with increasing elevation or annual precipitation (Table 6), estimated parameters for these two explanatory variables should be positive. Although there were no strong multicollinearities, there seemed to be a weak relationship among explanatory variables. In fact, as elevation increased maximum snow depth increased (Fig. 1, simple linear regression, p < 0.0005), and as maximum snow depth increased so did annual precipitation (Fig. 2, simple linear correlation, p < 0.0005). One of the ways to deal with multicollinearities is to omit explanatory variables if they are correlated with other explanatory variables which remain in the model (Quinn and Keough 2002). Since the model with the eighth smallest AIC does not include elevation or annual precipitation, it was chosen as the best weeding-duration model for Sakhalin fir plantations in Hokkaido (Table 9, Fig. 3). This model can be written as:

Years that weeding is necessary = Exp [-0.0289325 × site index + 0.0022502 × maximum snow depth (cm) + 0.0059264 × slope steepness (angle) + 2.085589 – 0.1006212 (if vegetation is *Sasa nipponica*) + 0.0072231 (if vegetation is *Sasa senanensis*) + 0.0800826 (if vegetation is *Sasa kurilensis*)].

Table 6. Estimates for parameters in generalized linear models with the single explanatory variables for number of years that weeding in *Abies sachalinensis* plantations is necessary (link function is log)

Variable in a model	Parameter estimate	*P* for model
Elevation	0.0002521	0.031
Slope steepness	0.006006	0.033
Maximum snow depth	0.0029306	<0.001
Annual precipitation	0.0001915	0.004
Geology (serpentine)	-1.609	0.006
Soil (low moor peat soil)	-0.6931	0.001
Site index	-0.04914	<0.001
Vegetation type		<0.001
S. nipponica	-0.18779	
S. senanensis	0.07331	
S. kurilensis	0.10704	

Table 7. Estimates for parameters in the generalized linear models with the smallest eight AICs for number of years that weeding in *Abies sachalinensis* plantations is necessary (link function is log)

Explanatory variables						AIC	*P* for model
Elevation	Slope	Maximum Snow depth	Annual precipitation	Site index	Vegetation type		
-0.000318	0.008235	0.003324	-0.0001263	-0.018310		3423.7	<0.0005
-0.000290	0.007890	0.002869	-0.0001117	-0.021130	*S. nipponica* -0.09151; *S. senanensis* 0.00640 *S. kurilensis* 0.06411	3423.8	<0.0005
-0.000279	0.007357	0.002612		-0.023578	*S. nipponica* -0.09860; *S. senanensis* 0.00255; *S. kurilensis* 0.06489	3423.9	<0.0005
-0.000370	0.007722	0.003566	-0.0001411			3424.2	<0.0005
-0.000305	0.007577	0.003049		-0.020684		3424.4	<0.0005
-0.000347	0.007228	0.003162	-0.0001313		*S. nipponica* -0.07868; *S. senanensis* 0.01563 *S. kurilensis* 0.06113	3425.0	<0.0005
-0.000363	0.006892	0.003290				3425.7	<0.0005
	0.005926	0.002250		-0.028933	*S. nipponica* -0.10062; *S. senanensis* 0.00722 *S. kurilensis* 0.08008	3426.0	<0.0005

Table 8. Tolerance and VIF of explanatory variables with continuous data

Explanatory variable	Tolerance	VIF
Elevation (m)	0.734	1.362
Slope (degrees)	0.893	1.120
Maximum snow depth (cm)	0.592	1.689
Annual precipitation (mm/year)	0.792	1.263
Site index (meters at 30 year, for city, town, or village)	0.820	1.219

Table 9. Estimates for parameters in the selected generalized linear model for number of years that weeding in *Abies sachalinensis* plantations is necessary (link function is log)

	Estimate	Standard error	*z* value	*P* value
Intercept	2.0855890	0.1680422	12.411	<0.0005
Slope	0.0059264	0.0029010	2.043	0.0411
Maximum snow depth	0.0022502	0.0003545	6.347	<0.0005
Site index (meters at 30 year, for city, town, or village)	-0.0289325	0.0113051	-2.559	0.0105
Vegetation – *S. nipponica*	-0.1006212	0.0455456	-2.211	0.0271
Vegetation – *S. senanensis*	0.0072231	0.0329938	0.219	0.8267
Vegetation – *S. kurilensis*	0.0800826	0.1020865	0.784	0.4328

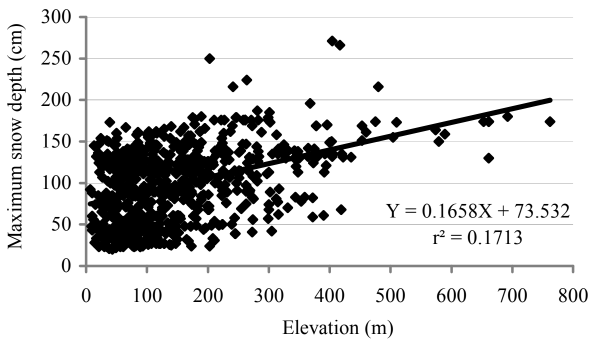

Fig. 1 Simple linear regression analysis of maximum snow depth as a function of elevation

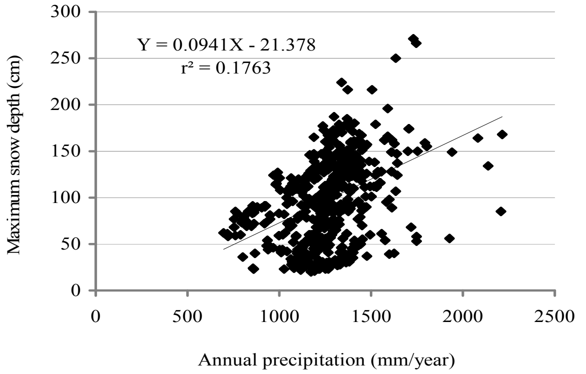

Fig. 2 Simple linear correlation between annual precipitation and maximum snow depth

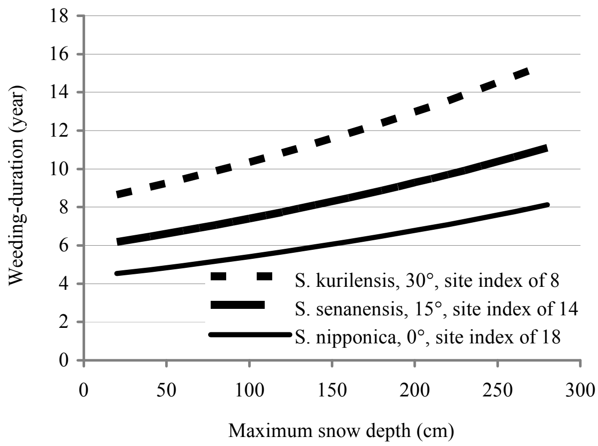

Fig. 3 The weeding-duration model for *Abies sachalinensis* plantations in Hokkaido

The model thus shows the following: the deeper the maximum snow depth, the longer weeding is necessary; the higher the site index, the shorter the weeding duration; and the steeper the slope of the plantation, the longer weeding is needed. Weeding duration is shorter in stands with *S. nipponica*, slightly longer with *S. senanensis*, and much longer with *S. kurilensis*. Figure 4 shows expected versus actual years that weeding is needed. Although the model is accurate (Y = nearly 1 X), the precision is not high (small r^2).

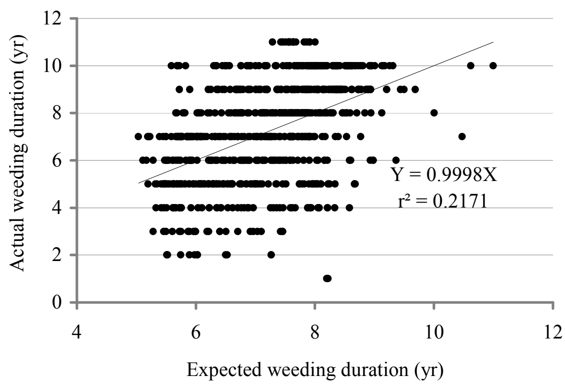

Fig. 4 Expected versus actual number of years that weeding is necessary

Discussion

The results of the present study imply that the number of years that weeding is necessary in Sakhalin fir plantations increases as the maximum snow depth and slope steepness increase, and decreases as the site index increases. Moreover, weeding duration is shorter in stands with *S. nipponica*, slightly longer with *S. senanensis*, and much longer with *S. kurilensis*. Since there was only one stand on serpentine rock and only nine stands with low-moor peat soils (Table 3), the effects of serpentine rock or

low-moor peat soils on weeding duration could not be discussed using the study data.

Weeding is carried out until planted trees become 60–80 cm higher than the competing vegetation (Nogami 1989). Thus, the number of years that weeding is needed is affected by the height of competing vegetation and the growth of planted trees. The number of years that weeding is needed is smaller in stands with a higher site index because trees grow faster in these locations, and thus planted trees are more rapidly freed from competition with vegetation.

The difference in weeding duration among different vegetation types can be explained by the difference in average vegetation height: *S. nipponica* is 30–100 cm, *S. senanensis* is 1.0–2.0 m, and *S. kurilensis* is 1.5–3.0 m (Samejima et al. 1993). The distribution of *Sasa* is strongly affected by snow depth: *S. nipponica* is found at low elevations in eastern Hokkaido with a maximum snow depth under 50 cm; *S. senanensis* is a more inland species found at higher elevations; and *S. kurilensis* is found at high elevations or on the Sea of Japan side of Hokkaido, where snow is very deep (Hokkaido Regional Forest District Office 1981; Toyooka et al. 1983; Nishiwaki and Konno 1989). Because the distribution of *Sasa* is strongly affected by maximum snow depth, there could be multicollinearity between maximum snow depth and vegetation type. However, in models with the eight smallest AICs, all the signs of estimated parameters for maximum snow depth and vegetation type were appropriate (Table 7). This implies that even in the same vegetation type, height of vegetation is affected by maximum snow depth. In general, *Sasa* species stop growing in mid-August to early September and overwinter with winter buds. Because buds above the maximum snow depth are likely to be injured by severe winter cold, heights of *Sasa* are affected by snow depth, even within the same species.

There could be two reasons why slope steepness affects weeding duration. First, vegetation from rows without site preparation tends to cover cleared rows. In general, site preparation and weeding in Sakhalin fir plantations is done in rows. Usually vegetation is cleared for 1.5–3.0 m widths, leaving 1.5–3.0 m of vegetation to protect planted trees from wind. On steeper slopes, *Sasa* in un-cleared rows tends to cover rows without vegetation where the trees are planted. Second, planted trees tend not to grow straight for about 10 years on steep slopes with deep snow because of the weight of the snow. Thus, such trees require longer time to overtop competing vegetation. However, the effect of slope steepness was not found to be significant in a weeding-duration model of Japanese larch (Nakagawa et al. 2011). This could be explained by different silvicultural characteristics of the two conifers. Usually all vegetation is cleared during site preparation for Japanese larch to avoid damage by the red-backed vole (*Clethrionomys rufocanus bedfordiae* Thomas). Moreover, Japanese larch is fast growing and thus there is less impact of slope steepness on its growth.

The weeding-duration model proposed in this study enables calculation of the number of years that weeding is necessary, based on the maximum snow depth, slope steepness, vegetation type, and site index of a locality. Although the model is accurate, it is not highly precise (Fig. 4) because several factors could not be included: quality of seedlings, annual changes in local climate, damage by pests, soil compaction during harvesting prior to re-planting, soil removal during site preparation, soil depth, past land use, and past events such as forest fires. Precision of the model could be improved if some of these factors were added to the explanatory variables. In addition, this study used the site index of a locality rather than that of each stand as an explanatory variable, although the site index of Sakhalin fir differ widely among stands in the same locality (Abe 1981).

While the precision of the model is not high (coefficient of determination: 0.217), it is much higher than that for Japanese larch (coefficient of determination: 0.046; Nakagawa et al. 2011). This is most likely due to differences in average weeding duration between Japanese larch (4.29 years; Nakagawa et al. 2011) and Sakhalin fir (7.19 years) (Table 1). Expected weeding duration in the proposed model is 3.5–6.5 years for Japanese larch (Nakagawa et al. 2011), but 4.5–15.5 years for Sakhalin fir (Fig. 3). Since actual weeding durations are always in integers, if the range is shorter the coefficients of determination become smaller.

Since the model precision is not high, determining when to stop weeding in each plantation using only the model is not recommended; weeding decisions should be judged from field observations in each stand. However, the weeding-duration model can still be useful. If the number of years that weeding is necessary is deduced from the model for a stand, instead of using the same number of years throughout Hokkaido, then current forest practice system models and cost–benefit analysis of plantations can be improved to reflect the environmental characteristics of each stand. Using this model, the economic advantages of planting Sakhalin fir in a stand on a gentle slope with a low maximum snow depth and in locations with a high site index can be quantitatively described.

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